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Miniaturization of Multiple-Layer Folded Patch Antennas

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***Abstract*—A new folded patch antenna with multiple layers was developed in this paper, by folding the patch in a proper way, and a highly miniaturized antenna can be realized. The multiple layer patch with 4-layer and 6-layer are designed and evaluated at 2.4 GHz, 915 MHz, and 415 MHz respectively. Then a 4 layer patch is fabricated and measured to validate the design method. The theoretical analysis, design and simulations, fabrications, as well as the measurements are presented in this paper. All the results show that the folded patch antenna is a good candidate in making a highly miniaturized compact antenna.**

***Index Terms*—Small antennas.**

I. Introduction

The antenna is an important component in wireless systems, and the demand for compact systems with stringent specifications for bandwidth and gain makes antenna size reduction a significant challenge. It is with no doubt that the antenna miniaturization is one of the key technologies in designing successful wireless networks, and a lot of antenna miniaturization techniques have been developed [1]-[5]. In this paper, the multiple layer folded patch antenna is studied and compact antenna designs are developed. The conventional rectangular patch antenna resonates when its length is half of the wavelength. By adding a shorting wall at the center of the patch, the antenna size can be reduced to a quarter of the wavelength. Moreover, by folding the wall-shorted patch, the overall size of the two layer patch antenna becomes one eighth of the wavelength [6]-[8]. In this paper, the multiple layer folded patch antenna is further developed by folding the patch in a proper way, which results in a highly miniaturized antenna. Multiple layer folded patch antennas with 4 and 6 layers are designed and evaluated at 2.4 GHz, 915 MHz, and 415 MHz respectively, using the commercial software package HFSS [10]. Then a 4-layer patch for 415 MHz is fabricated and measured to validate the design method. The theoretical analysis, numerical simulations, manufacturing issues, as well as measurements will be presented in this paper.

II. Theoretical Analysis: Transmission Line Model

The transmission line model [8]-[9] is used to analyze the multiple layer patch. For an N layer patch, each layer can be viewed as a section of the transmission with length L and the characteristic admittance Y_0, as shown in Fig. 1 and Fig. 2,

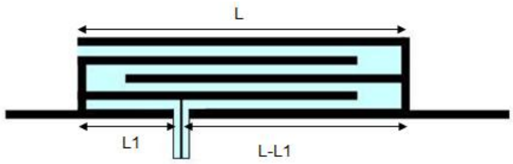

Fig. 1. An example of the multiple-layer folded patch (4 layers).

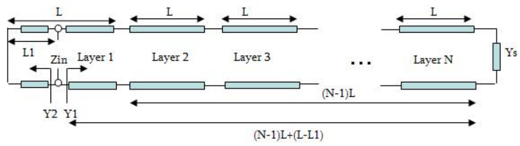

Fig. 2. The transmission line model of the multiple-layer patch antenna.

where N is the numbers of layers, L_1 is the feed position of the antenna, and Y_0 is characteristic admittance of each layer. The input impedance at the feed point can be expressed as

$$Z_{in} = jX_f + Z_A, \tag{1}$$

where X_f is the reactance of the feed probe. X_f is given by

$$X_f = \frac{\omega\mu_0 h}{2\pi}[ln(\frac{2}{\beta r}) - 0.57721], \tag{2}$$

where $\beta = 2\pi/\lambda_0$, r is the radius of the probe, and Z_A is antenna impedance, $Z_A = 1/Y_A$. The admittance Y_A can be found from Y_1 and Y_2, $Y_A = Y_1 + Y_2$, which are

$$\begin{cases} Y_1 = Y_0\frac{Y_s + jY_0\tan\beta[(N-1)L+(L-L_1)]}{Y_0 + jY_s\tan\beta[(N-1)L+(L-L_1)]} \\ Y_2 = Y_0\frac{1}{j\tan(\beta L_1)} \\ Y_A = Y_0\frac{Y_s + jY_0\tan\beta[(N-1)L+(L-L_1)]}{Y_0 + jY_s\tan\beta[(N-1)L+(L-L_1)]} + \frac{Y_0}{j\tan(\beta L_1)} \end{cases}, \tag{3}$$

where N is the number of layers, L_1 is the feed position of the antenna, Y_0 is characteristic impedance of each layer, and Y_s is the admittance of the equivalent radiation slot of the patch. We assume that each layer of the folded patch is of equal thickness h, and thus the characteristic impedance of each layer are the same approximately. Y_s can be determined from $Y_s = G_s + jB_s$, and

$$Gs = \begin{cases} \frac{1}{90}(\frac{W}{\lambda_0})^2, \ W \le 0.35\lambda_0 \\ \frac{1}{120}(\frac{W}{\lambda_0}) - \frac{1}{60\lambda_0^2}, \ 0.35\lambda_0 \le W \le 2\lambda_0 \\ \frac{1}{120}(\frac{W}{\lambda_0}), \ 2\lambda_0 \le W \end{cases}, \tag{4}$$

TABLE I
PROBE-FED MULTIPLE LAYER FOLDED PATCH ANTENNA (FREQUENCY= 2400MHZ).

	Antenna Dimension [mm]	Feed Position $L_1[mm]$	Ground Size [mm]	Bandwidth (BW@-10 dB)	Efficiency [%]	Directivity [dBi]	Gain [dBi]
Design1 (2-layer design)	$L_{patch} = 15.5mm = 0.124\lambda_0$ $W_{patch} = 17.5mm = 0.14\lambda_0$ $H_{patch} = 2h = 3mm$ $L_{gap} = 1mm, h = 1.5mm$	2.3 mm	21.5 mm*21.5 mm	12 MHz	89.5%	2.07 dBi	1.59 dBi
Design2 (4-layer design)	$L_{patch} = 8.875mm = 0.071\lambda_0$ $W_{patch} = 8.75mm = 0.07\lambda_0$ $H_{patch} = 4h = 6mm$ $L_{gap} = 1mm, h = 1.5mm$	2 mm	13.8 mm*12.75 mm	12 MHz	87.5%	1.73 dBi	1.16 dBi
Design3 (6-layer design)	$L_{patch} = 5mm = 0.04\lambda_0$ $W_{patch} = 6mm = 0.048\lambda_0$ $H_{patch} = 6h = 3mm$ $L_{gap} = 1.5mm, h = 0.5mm$	0.9 mm	11 mm*10 mm	4 MHz	62%	1.56 dBi	-0.52 dBi

TABLE II
PROBE-FED MULTIPLE LAYER FOLDED PATCH ANTENNA (FREQUENCY= 900MHZ).

	Antenna Dimension [mm]	Feed Position $L_1[mm]$	Ground Size [mm]	Bandwidth (BW@-10 dB)	Efficiency [%]	Directivity [dBi]	Gain [dBi]
Design4 (2-layer design)	$L_{patch} = 39.12mm = 0.117\lambda_0$ $W_{patch} = 41.625mm = 0.125\lambda_0$ $H_{patch} = 2h = 3mm$ $L_{gap} = 2mm, h = 1.5mm$	6.5 mm	45.12 mm*45.625 mm	12 MHz	95.5%	2.2 dBi	2 dBi
Design5 (4-layer design)	$L_{patch} = 22.83mm = 0.069\lambda_0$ $W_{patch} = 21.47mm = 0.065\lambda_0$ $H_{patch} = 4h = 6mm$ $L_{gap} = 1.5mm, h = 1.5mm$	3.5 mm	27.4 mm*25.8 mm	1.2 MHz	58%	2 dBi	-0.4 dBi
Design6 (6-layer design)	$L_{patch} = 13mm = 0.039\lambda_0$ $W_{patch} = 14mm = 0.042\lambda_0$ $H_{patch} = 6h = 3mm$ $L_{gap} = 1.5mm, h = 0.5mm$	1.9 mm	15.6 mm*16.8 mm	1.5 MHz	22.5%	1.9 dBi	-4.6 dBi

where G_s and B_s are the conductance and susceptance respectively, and W is the width of the patch. For the electrically small antenna, Y_s is much smaller than Y_0, and the effect of Y_s is small. For simplicity, we assume that its influence can be ignored, as well as the probe reactance. Hence, at the resonance there is the condition that $Y_A = 0$, which leads to

$$\frac{Y_0}{\tan(\beta L_1)} = Y_0 \tan\beta[(N-1)L + (L - L_1)] \tag{5}$$

Using the relation that $tan^{-1}(\beta L_1) = tan(\pi/2 - \beta L_1)$, the approximate resonance length L of the N-layer folded patch antenna is found to be

$$L = \frac{\lambda_0}{4N\sqrt{\varepsilon_r}}, \tag{6}$$

where λ_0 is the wavelength in free space and ε_r is the dielectric constant of the substrate. The Equation (6) is an important result of this paper. For the 4-layer patch, the overall length of the patch is $L = \frac{\lambda_0}{16\sqrt{\varepsilon_r}}$. For the 6-layer patch, the resonance length becomes to $L = \frac{\lambda_0}{24\sqrt{\varepsilon_r}}$.

III. ANTENNA DESIGNS

Our purpose here is to design the highly miniaturized antenna, and folded patch antennas are designed and evaluated at 2400 MHz, 900 MHz, and 415 MHz for different applications. For each frequency, three different versions are designed, which are 2-layer, 4-layer, and 6-layer folded antennas, and the antenna performance is given for each case. The geometry and design variables of the folded patch are illustrated in Fig. 3.

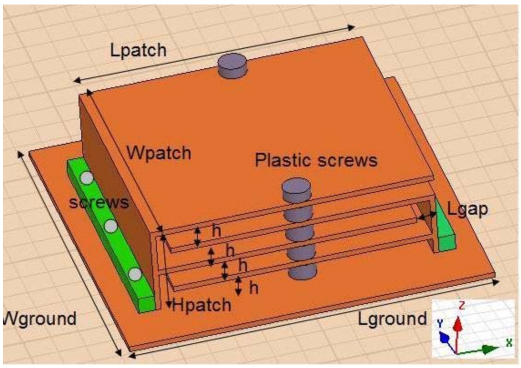

Fig. 3. Geometry of design variables for 4-layer folded patch (in HFSS).

Table I shows the folded patch antennas which are designed to operate at the frequency of 2400 MHz, and also predicts the performance provided by HFSS, including the bandwidth and radiation efficiency. For the four layer case in design 2, the antenna dimension is $8.875mm \times 8.75mm \times 6mm$, and the electrical size of the patch length is reduced to 0.071 λ_0 ($ka = 0.23$), and at the same time the ground plane size is also limited to be as small as possible. The bandwidth is found to be 12 MHz and the radiation efficiency is 87.5%. For the 6-layer case, in design 3, the antenna is of the dimension $5mm \times$

TABLE III
PROBE-FED MULTIPLE LAYER FOLDED PATCH ANTENNA (FREQUENCY= 415MHZ).

	Antenna Dimension [mm]	Feed Position $L_1[mm]$	Ground Size [mm]	Bandwidth (BW@-10 dB)	Efficiency (for ground size 1)	Efficiency (for ground size 2)
Design7 (2-layer design)	$L_{patch} = 50.2mm = 0.069\lambda_0$ $W_{patch} = 46.7mm = 0.065\lambda_0$ $H_{patch} = 4h = 12mm$ $L_{gap} = 2.5mm, h = 3mm$	8.6 mm	Ground size 1: 60.25 mm*55.4 mm Ground size 2: 200 mm*200 mm	1.2 MHz	52%	67%

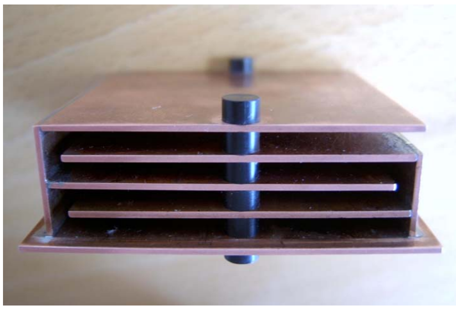

Fig. 4. The fabricated 4-layer patch antenna with a small ground plane, in design 7, operated at 415 MHz

$6mm \times 6mm$. The electrical length of the patch length is 0.04 λ_0 ($ka = 0.126$), and the bandwidth is found to be 4 MHz and the radiation efficiency is 62%. The bandwidth is small in design 3 and this is due to a smaller thickness is used between each layer. The radiated power is reduced as the antenna size decreases, and thus the radiation efficiency for design 3 must be lower than that for design 2. Hence, the ultra small antenna is possible to be realized by this folded patch, and a high fabrication accuracy is required since the antenna is both electrically and mechanically small at this frequency.

Table II gives the folded patch designs at 915 MHz , as well as their bandwidth and radiation efficiency. Similarly, the ground plane size is controlled as small as possible. For the four layer case, design 5, the antenna dimension is $22.83mm \times 21.47mm \times 6mm$, that is the electrical length of the patch is reduced to about 0.068 λ_0 ($ka = 0.21$). The bandwidth is found to be 1.2 MHz and the radiation efficiency is 58%. The maximum gain is -0.4 dBi. For the 6-layer case, in design 6, the antenna dimension is decreased to $13mm \times 14mm \times 6mm$, and the electrical size of the patch length is 0.039 λ_0 ($ka = 0.12$). The bandwidth is found to be 1.5 MHz and the radiation efficiency is 22.5%. The maximum gain is -4.6 dBi. These results shows that the folded patch antenna is a good candidate in making the highly miniaturized compact antenna, while we should also keep in mind that the mechanism of the miniaturization is the tradeoff among antenna size and performance.

Table III illustrates the folded antenna designed to operate at 415 MHz, which is a 4-layer patch antenna. This antenna is of the dimension of $50.2mm \times 46.7mm \times 12mm$, and the electrical size of the patch length is 0.069 λ_0 with ka is equal to 0.22. The bandwidth is 1.2 MHz and the radiation efficiency is 67%.

IV. ANTENNA FABRICATION

In order to validate the above performance predicted by the numerical simulations, the antenna in design 7 which operates at 415 MHz is fabricated at our workshop. As shown in Fig. 4, this antenna uses 1 mm thickness copper plate as its each layer. Several practical issues are involved, which should be solved carefully during the fabrication and steps can be given as follows. First, each layer and the side wall are cut into rectangular pieces accurately, and then these pieces can be combined together by the soldering. In order to control the thickness between each layer, we make several plastic screws in our workshop with its thickness is accurately controlled, and then we put two of them between the each layer. However, its influence on the resonance frequency must be taken into account. Second, another important step is the connection between the antenna and the ground plane. In our design, the antenna is attached to the ground by using the screws rather than the soldering, and we did it in this way because we can replace the ground plane easily, which provides us the convenience to evaluate the size influence of different ground plane. The same 4-layer folded patch antenna but with a different ground is shown in Fig. 5, in which the ground plane is much larger. Since the ground plane has an important influence on the antenna impedance, the feeding point position must be adjusted accordingly when different ground plane is used. Later, the large ground plane is used in the measurement in order to avoid the cable influence. Third, about the antenna feeding, a specially smart SMA connecter is used as the feed probe, whose inner conductor is possible to be taken away from the SMA easily. We first solder the inner conductor to the feed point on the patch, and then attach the antenna and the ground. Then screw the SMA frame to the ground, and combine the inner and the outer of the SMA at the same time. The antenna assembling process is done by the above steps during which the accuracy can be controlled as much as possible.

V. ANTENNA MEASUREMENT

In order to compare the antenna performance with the numerical simulation results, this 4-layer design at 415 MHz is measured with respect to impedance and radiation properties. The s parameter S_{11} was measured first by using the network analyzer HP 8720D, with an absorber placed in front of the antenna. The simulated and measured S_{11} for the 4-layer patch antenna are presented and compared in Fig. 6. While the simulated resonance frequency is 415 MHz, the measured resonance frequency is 416.7 MHz, and the deviation is only

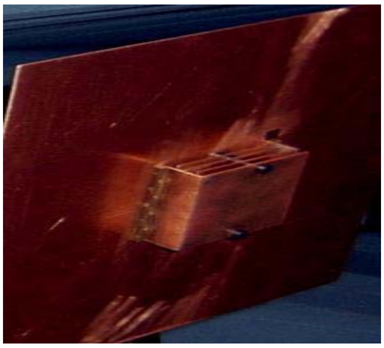

Fig. 5. The fabricated 4-layer patch antenna with a large ground plane, in design 7, operated at 415 MHz

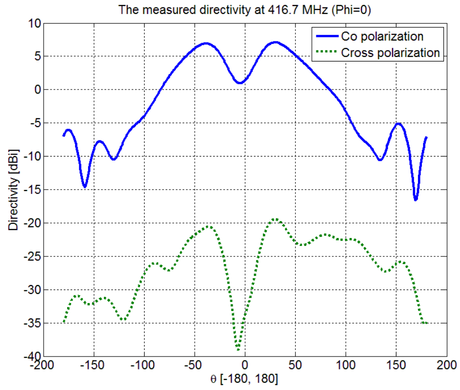

Fig. 7. The measured directivity versus θ (for $\phi = 0°$), which is a 4-layer folded patch antenna at 415 MHz.

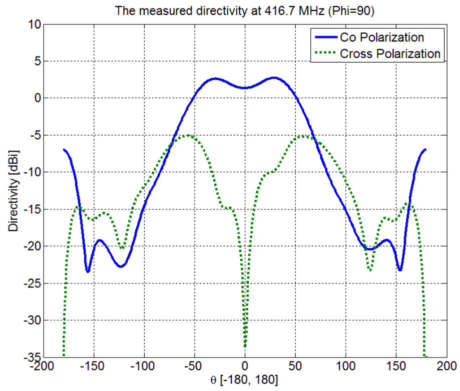

Fig. 8. The measured directivity versus θ (for $\phi = 90°$), which is a 4-layer folded patch antenna at 415 MHz.

0.4 %. The simulated and measured -10dB bandwidth are 1.12 MHz and 1.08 MHz respectively, and the difference is thus only 0.04 MHz.

The radiation measurement is performed in the Radio Anechoic Chambers at DTU, which is called DTU-ESA Spherical Near Field Antenna Test Facility. The measured directivity versus θ (for $\phi = 0°$ and $\phi = 90°$) at 415 MHz are shown in Fig. 7 and Fig. 8 respectively. The efficiency of the antenna was measured by using the substitution method, and found to be 59%, which is reasonably close to the simulated efficiency 67%. The gain is acceptable for the antenna of such small dimension.

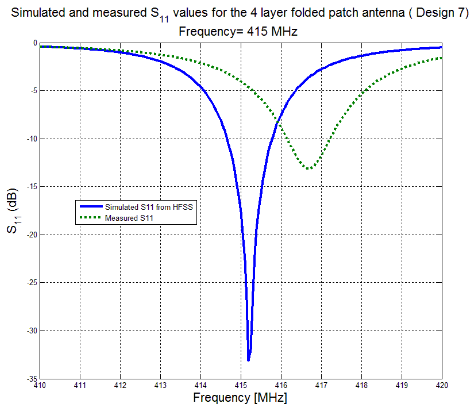

Fig. 6. The simulated and measured S11 for the 4-layer patch antenna, which is designed to operate at 415 MHz.

VI. Conclusions

Multiply layer patch antennas are developed at three frequencies, and the performance of these highly miniaturized antennas are presented. A 4-layer folded patch operated at 415 MHz is fabricated and all practical issues are solved and discussed. Then the antenna measurement is performed, and measured results agree well with numerical simulations.

In this work, the folded patch antennas are designed in the vacuum environment for simplicity, and further development will be focused on the combination of using the high dielectric constant substrate. Moreover, the low loss magneto-dielectric material is also a good candidate to be evaluated as the patch substrate, which should result in a bandwidth improvement.

Acknowledgment

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